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Cross-layer Approach to Low Energy Wireless Ad Hoc Networks

By

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Motivation

- Wireless ad-hoc and sensor networks are energy constrained due to battery powered nodes
 - Limited battery capacity, inability to recharge batteries in nodes (such as sensors deployed in remote regions or battlefield) limit the nodes' lifetime
- Traditional single layer approach for energy conservation are limited in performance
 - Single-layer optimization results may sometimes affect overall performance due to conflicting factors
 - With power limiting the performance for many portable systems, any amount of additional power saved will be useful

Need for cross-layer design approaches in energy conservation!!!

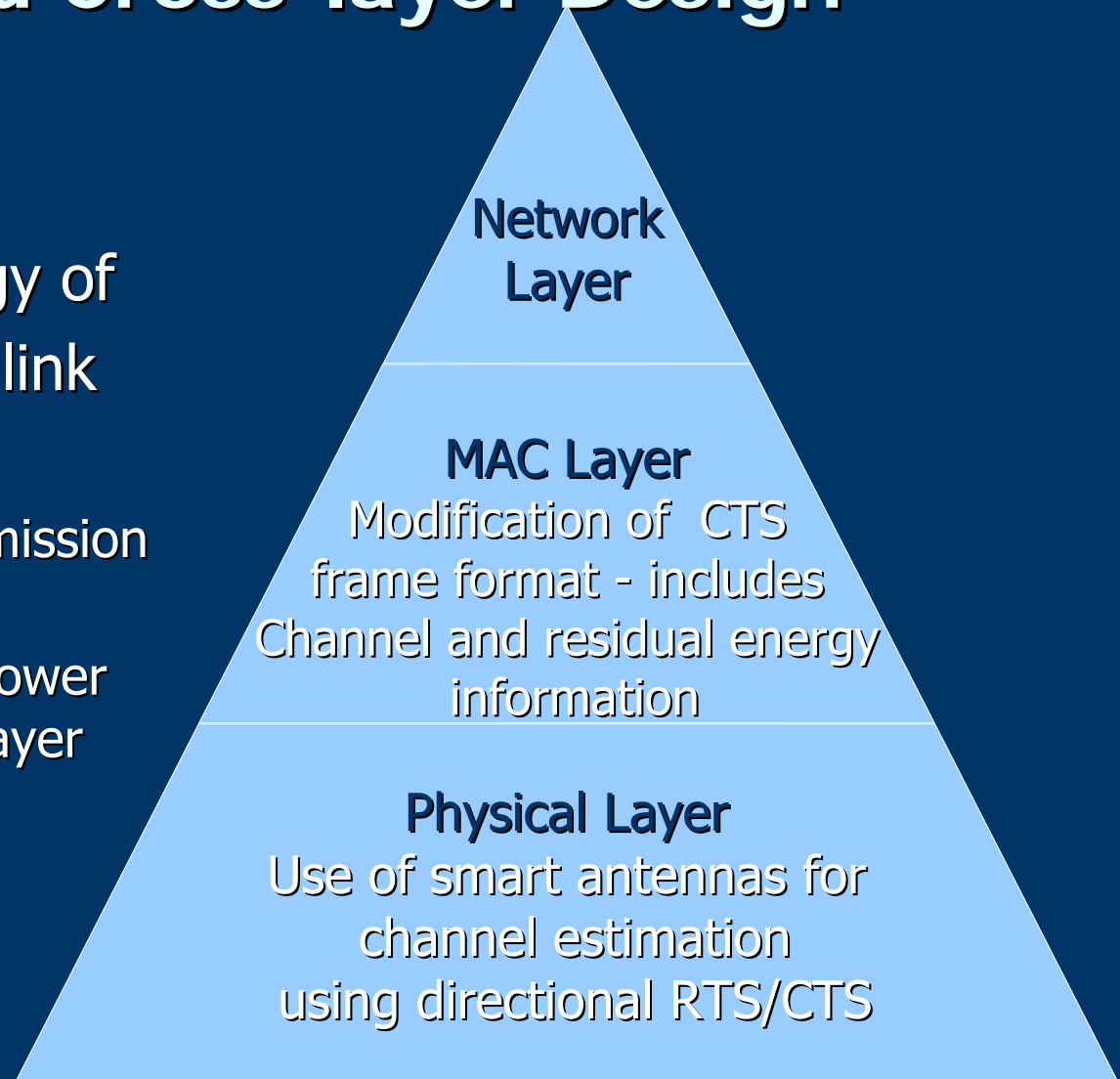
Objective

- Develop a cross-layer design approach for improved energy conservation in wireless ad-hoc and sensor networks
- Analyze the impact of cross-layer approach on energy consumption due to data retransmissions and collisions by developing new energy models

Proposed Cross-layer Design

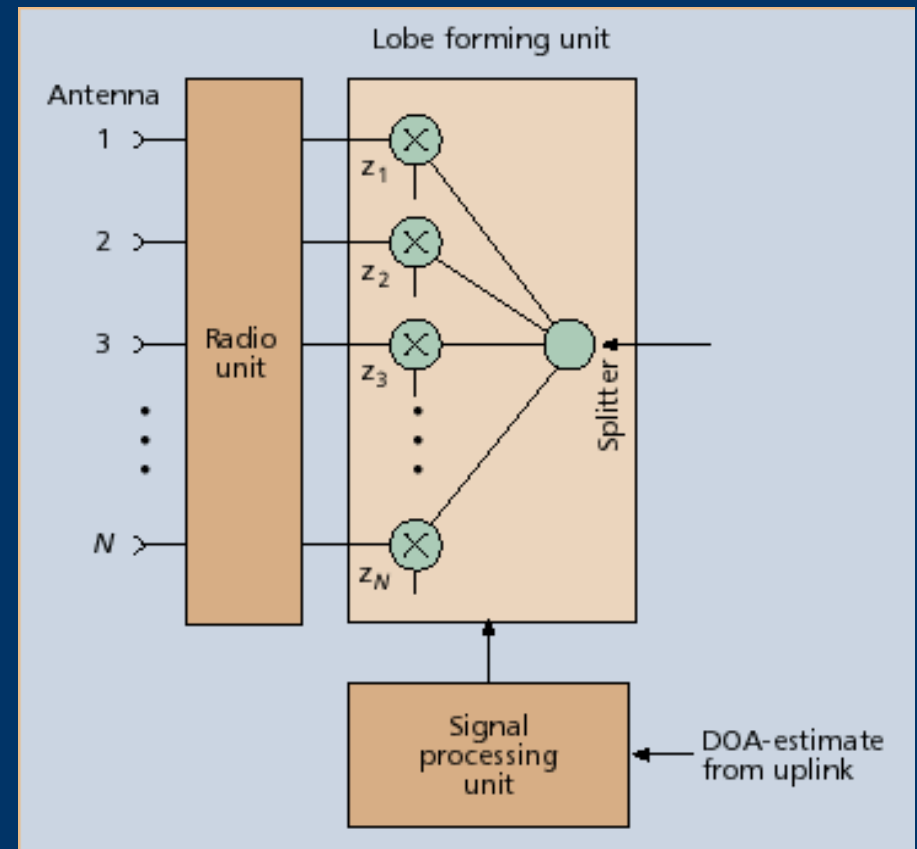
Joint estimate of channel quality and residual energy of the next hop node at the link layer is used for

- Determining data transmission at network layer and
- Adaptive transmission power control at the physical layer



Maximum SINR beamforming Technique (Physical layer)

- Weights z_i of the antenna elements chosen such that signal-to-interference noise ratio (SINR) at receiver is maximized
- Suppresses the interference and noise in the channel
 - Hence reduces collisions in channel due to interference



Modifications of CTS frame (MAC layer)

- MAC layer performs channel estimation using Directional RTS (DRTS) to obtain the quality of the channel
- Link Aware Metric (LAM) at the MAC layer stores the channel information obtained
- Residual energy aware metric (REM) indicates the residual energy available at the next hop node
- The LAM and REM information are fed back to the receiver in the CTS control packet

Modified CTS frame format:

Frame control	Duration	RA	CRC	LAM	REM
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Algorithm Steps

Step1:

Direction Of Arrival (DOA) estimation during route discovery phase



Broadcast RREQ packets

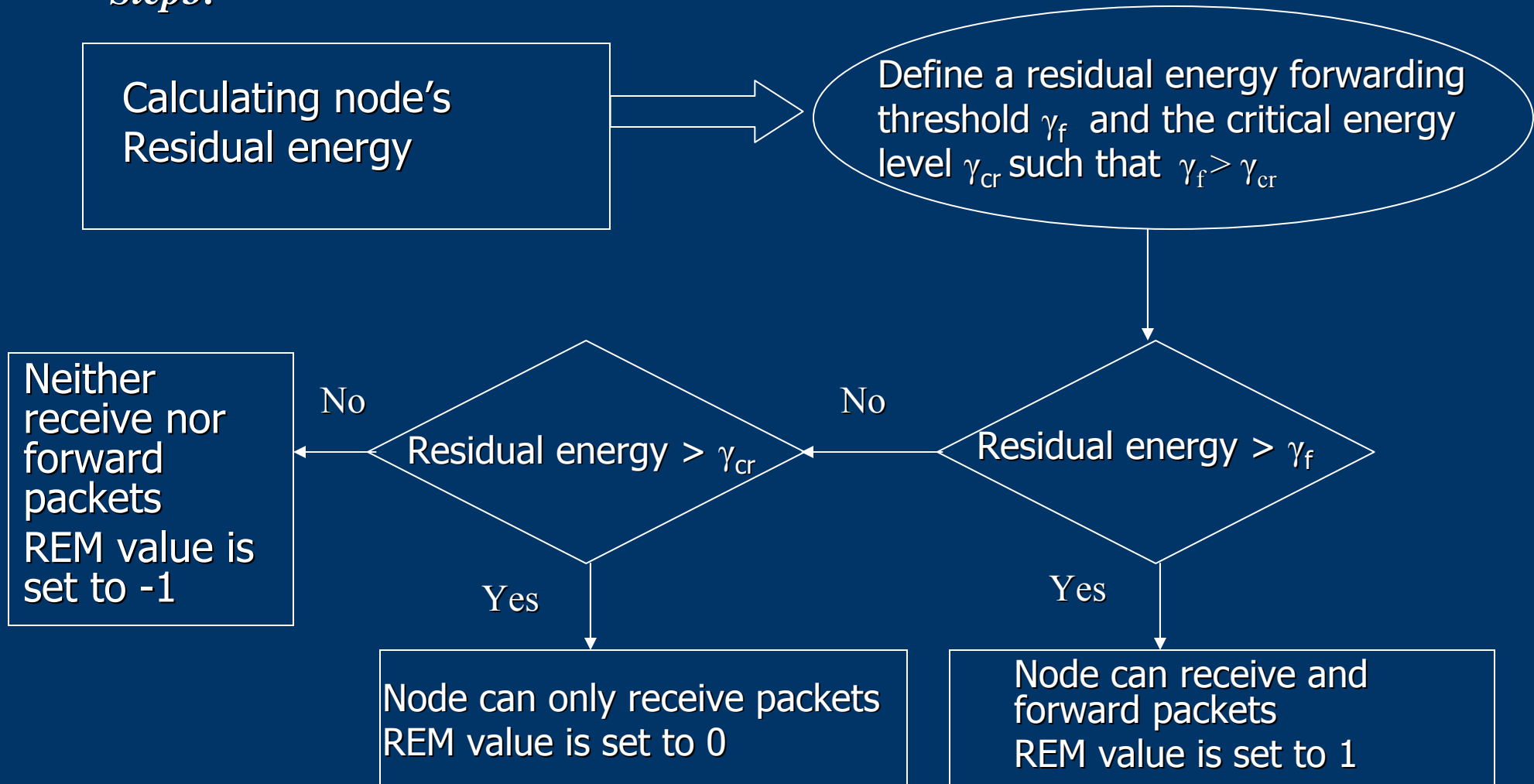
- Intermediate nodes store angular information by performing DOA estimation
- Directionally transmit RREP packets using the information obtained

Step2:

Estimation of channel quality



- Transmit directional RTS using direction information obtained from the network layer above
- Calculate SINR of the received RTS frame
- *If* SINR > threshold, set LAM value '1', *else* set to '0'

Step3:

Step4:

Directional CTS feedback



Link Aware metric (LAM) and Residual Energy metric (REM) are included in the CTS frame format and directionally fed back to the sender

Step5:

Adaptive transmission power control



If CTS is received with REM value set to 1, but LAM value set to '0',

- increase the signal transmission power to overcome the interference and noise in the channel &
- retransmit DRTS to achieve the desired SINR at the receiver

Step6:

Decision to transmit or
drop data



- If LAM is set to '0', it indicates a poor channel quality
 - Retransmit RTS with increased signal power

- If REM is set to -1,
 - do not transmit data and
 - inform network layer to choose another route.

- If LAM and REM values are both set to '1', then transmit data

Analysis of energy conservation

Energy model

Our approach:

- Develop and analyze energy models that consider energy consumed due to
 - media contention
 - messages lost due to collision
 - wireless transmission environment
- Energy consumed per transmission depends on the wireless transmission environment
- Probability of collisions is modeled as a function of the density of nodes in the coverage area

Energy model (continued)

Energy required to transmit RTS, CTS or data packets is modeled as

$$\text{Energy consumption per packet } E = P * \text{size} * d^a$$

where P = transmission power,
size = number of bytes in the control frame or the data packets,
 d = distance between transmissions; a =attenuation factor.

Total energy consumption of a node

$$E_{\text{total}} = E * \text{no. of retransmissions}$$

Probabilistic analysis : Define collision of packets as a function of node density

Define the number of nodes in the transmission range of the sender node as N .

Probability that a node is transmitting packets = p

Probability that no node in the coverage area transmits is $(1-p)^N$

Probability of RTS collision = $\Pr(\text{rts_failure}) =$
 $\Pr(\text{more than 1 node is transmitting in the same range}) =$
 $1 - (1-p)^N$

Av. number of RTS retransmissions $n_r = \sum_{i=1}^n i * \Pr_i(\text{rts_failure})$

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Scenario 1: Energy consumed in unsuccessful attempts to acquire channel

- **RTS sent, but CTS not received**
- Possible reasons :
 - ❖ Collision of RTS packets due to interfering sources
 - ❖ Receiver involved in another communication
 - ❖ Transmission power is low or channel noise is high
- Solution : Retransmission of RTS (maybe with higher transmission power)
- Energy consumed in transmitting RTS packet is

$$E_{\text{RTS}} = P_{\text{trans_RTS}} * \text{size (RTS_frame)} * d^{\alpha}$$
- Total Energy consumed by the node for channel acquisition

$$\text{Energy}_{\text{total}} = n_r * E_{\text{RTS}}$$

Energy conservation

➤ Smart directional antennas at the physical layer helps in directional transmissions of RTS packets. This reduces the transmission power needed to transmit the RTS frame.

$$\text{i.e. } P_{\text{trans_RTS}} (\text{smart antennas}) < P_{\text{trans_RTS}} (\text{omni})$$

➤ Small number of nodes (N) transmitting in the coverage area leads to reduced interference .

➤ Low value of N leads to lower probability of RTS collision leading to a decrease in the number of RTS retransmissions.

➤ Hence, energy spent in RTS transmissions is reduced using smart directional antennas.

Scenario 2: Energy consumed in data re-transmissions due to bad channel quality or due to unavailable energy resources at nodes

Data lost after RTS-CTS handshake

Solution : retransmit RTS-CTS-data

Energy spent in transmitting a data packet

$$E_{\text{data}} = P_{\text{trans_data}} * \text{size (data)} * d^{\alpha}$$

Energy consumed in transmitting RTS packet is

$$E_{\text{RTS}} = P_{\text{trans_RTS}} * \text{size (RTS_frame)} * d^{\alpha}$$

Case 1: Without cross-layer approach

$$\text{Average number of data retransmissions } n_d = \sum_{i=1}^n i * \text{Pr}_i(\text{data lost})$$

$$\text{Average number of RTS retransmissions } n_r = \sum_{i=1}^n i * \text{Pr}_i(\text{rts_failure})$$

$$\text{Total energy consumed by the node} = n_r * E_{\text{RTS}} + n_d * E_{\text{data}}$$

Case 2: With cross-layer approach

With cross-layer approach, we obtain the information on channel quality and the residual energy of nodes.

Probability of transmitting data is the probability that the channel quality is good and there is sufficient energy available at node level.

$\text{Pr}(\text{Transmit data}) = \text{Pr}(\text{channel is good}) \cdot \text{Pr}(\text{energy available})$

$\text{Pr}(\text{channel is good})$ is estimated by the LAM value

$\text{Pr}(\text{energy available})$ is estimated by the REM value

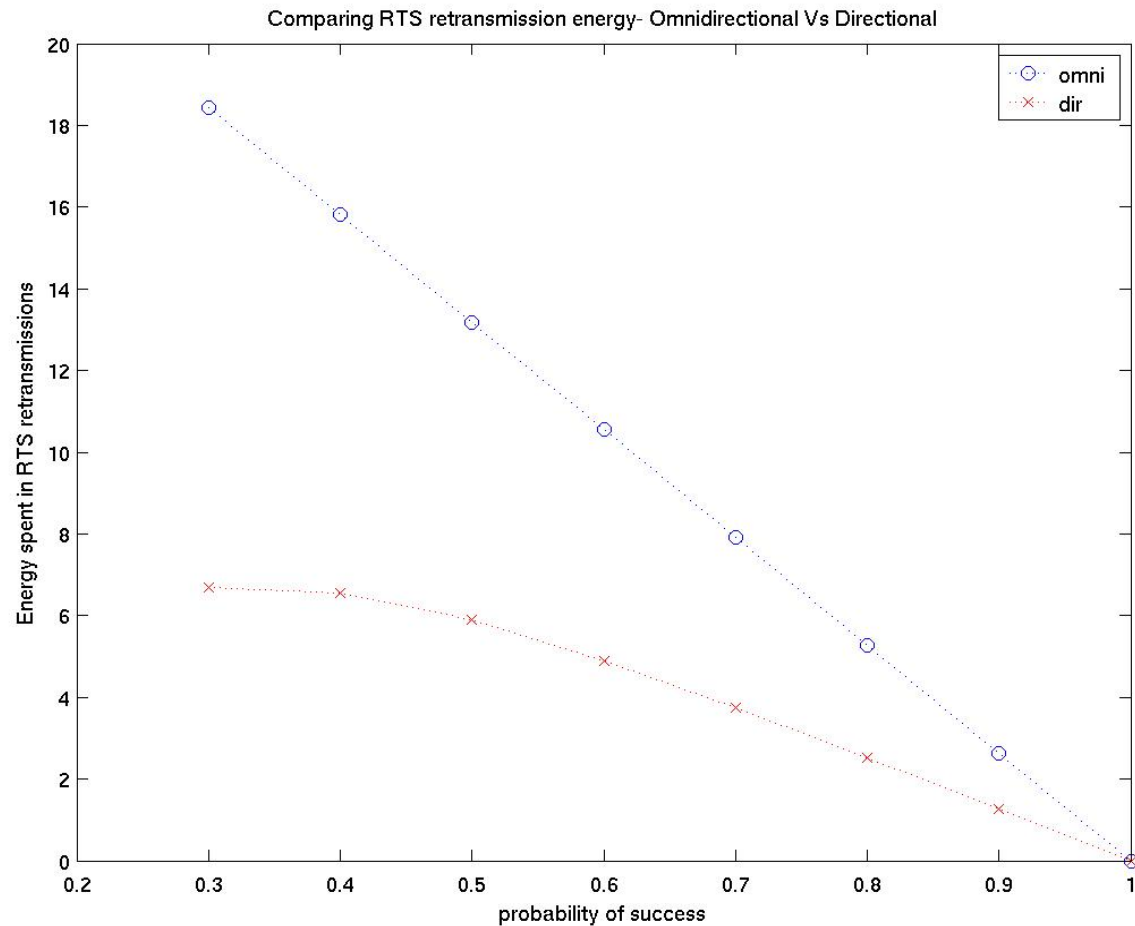
Total energy consumed by the node =

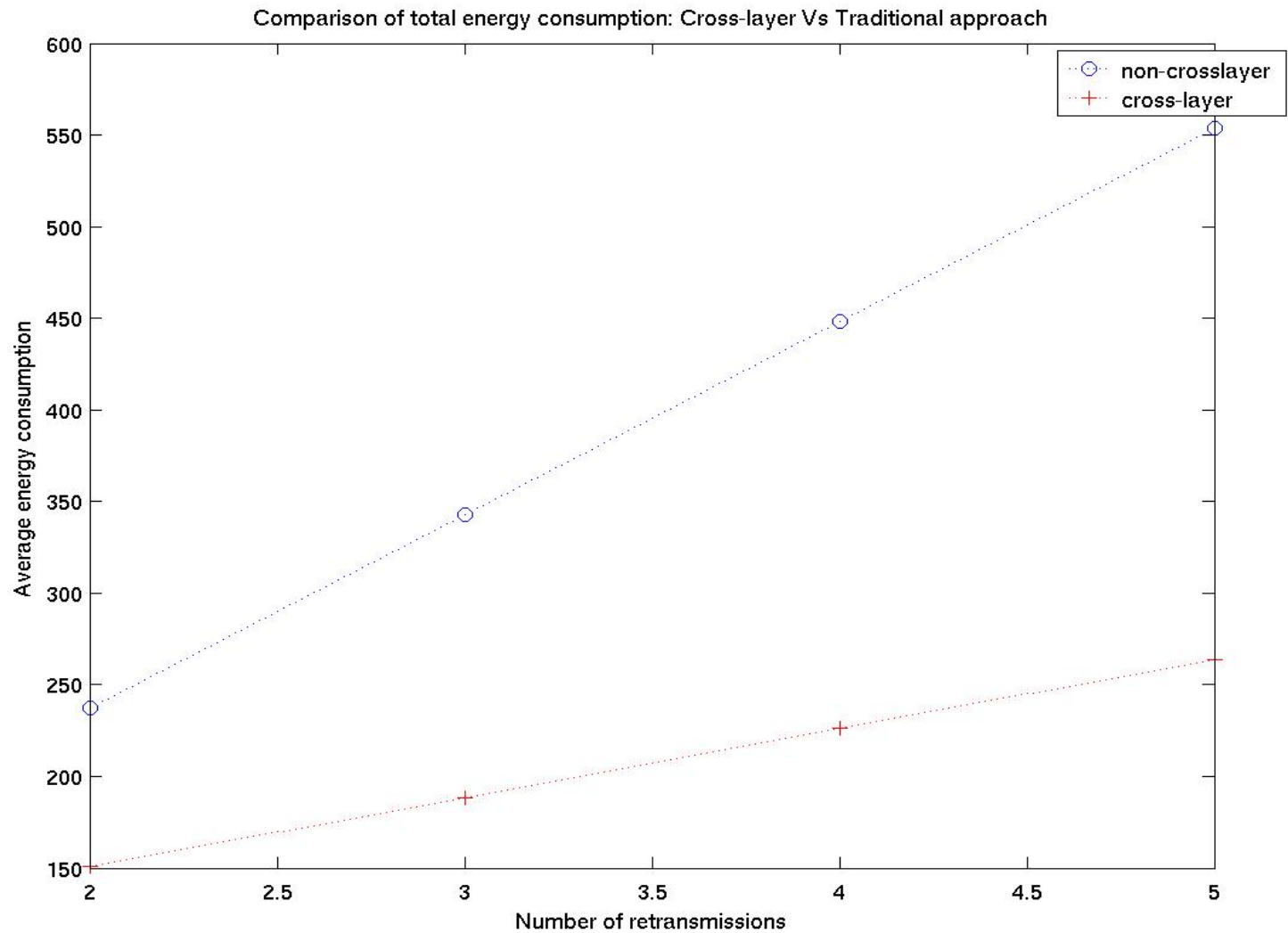
$$n_r * E_{\text{RTS}} + \sum_{i=1}^n \text{Pr}_i(\text{Transmit data}) * E_{\text{data}}$$

Cross-layer Interactions

- We utilize the interactions between the physical-link-network layers
- The channel quality estimated using DRTS/DCTS packets at the link layer helps in determining the transmission power of the node at the physical layer
- Based on the varying wireless transmission environment, the channel information obtained at the link layer is used at the network layer to determine data transmission along a route
- Similarly, the residual energy information of the next hop node obtained at the link layer is used at the network layer to find efficient routes

Simulation Results





Conclusions & Future Work

- Use of smart antennas for RTS/CTS and data transmission reduces the level of interference with the neighboring nodes and hence reduces collisions
- Cross-layer design that uses the channel quality and the residual energy information reduces the unnecessary energy spent in data retransmissions
- The channel information is used to adaptively control the transmission power and determine the optimum power needed for the communication
- Reduction in collisions, retransmissions and transmission power leads to overall energy conservation
- Future work: Propose a traffic adaptive approach to turn the node's radio ON or OFF; investigate the performance trade-offs in energy costs involved in computation and communication processing